PARTICLE PENETRATION THROUGH WINDOWS

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ABSTRACT
This study aims to characterize the fractional penetration of airborne particles through windows, one of the important sites of air leakage through building envelopes. Two aluminum windows were evaluated, one with weatherstripping and one without. For each experiment, a finished window was mounted and sealed in a plywood panel that separated two well-mixed compartments. A small pressure difference was established between the compartments to induce a constant rate of airflow through leakage paths in the window. Particles were injected into one chamber and their concentrations were measured in both chambers. Two methods were employed to evaluate the size-resolved particle penetration: a steady-state method and a dynamic, concentration growth method. The results indicate that airborne particles of 0.2 to 3 μm penetrate through both test windows fairly effectively, while significant particle losses are observed for particles smaller and larger than this range.

INDEX TERMS
Aerosols, Air pollutant transport, Particles, Pollutant penetration, Windows

INTRODUCTION
Windows are important contributors to air leakage in building envelopes. The investigation of air leakage through windows has been of interest owing to concerns such as reduced thermal comfort from cold drafts, increased energy consumption, and condensation problems. Less studied is the concern that air leakage through windows can also permit the penetration of ambient airborne particles into indoor environments, causing exposures that may have adverse health effects or contribute to material damage. For low-rise buildings, studies have indicated that most air leakage arises from openings in ceilings and walls; window and door components contribute about twenty percent to total air infiltration (Tamura, 1975; ASHRAE, 1993; Reinhold and Sonderegger, 1983). The extent of particle penetration through building cracks of well-defined geometry and through wall cavities has been modeled (Liu and Nazaroff, 2001). Experimental work using building-material cracks of idealized geometry has shown generally good agreement with model predictions (Liu and Nazaroff, 2002). However, for building components possessing complicated leakage paths, such as windows and other fenestration products, it seems more practical to develop an understanding of particle penetration by conducting experiments in the laboratory or in the field.

We know of no published study that evaluates the performance of windows with respect to the infiltration of ambient particles. In this study, particle penetration was measured in laboratory experiments for two windows. We believe that the methods used here can be applied to study particle penetration through other fenestration products (doors, curtain walls, etc).

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METHODS

Two operable, used aluminum sliding windows were obtained for the experiments; one is equipped with tubular gasket weatherstripping between moving sash and bottom frame (commercial class; designated as Wc), and the other is not weatherstripped (residential; Wr). Both windows have bristles between the sash and the frame to reduce air leakage. In addition, Wc has a wooden case that surrounds the aluminum perimeter frame closely. The commercial window was also tested with the joints between the wooden case and aluminum frame sealed by tape (test designated as Wc'). The frame sizes of Wr and Wc are 48.7 × 63.8 cm and 58.9 × 58.6 cm, respectively.

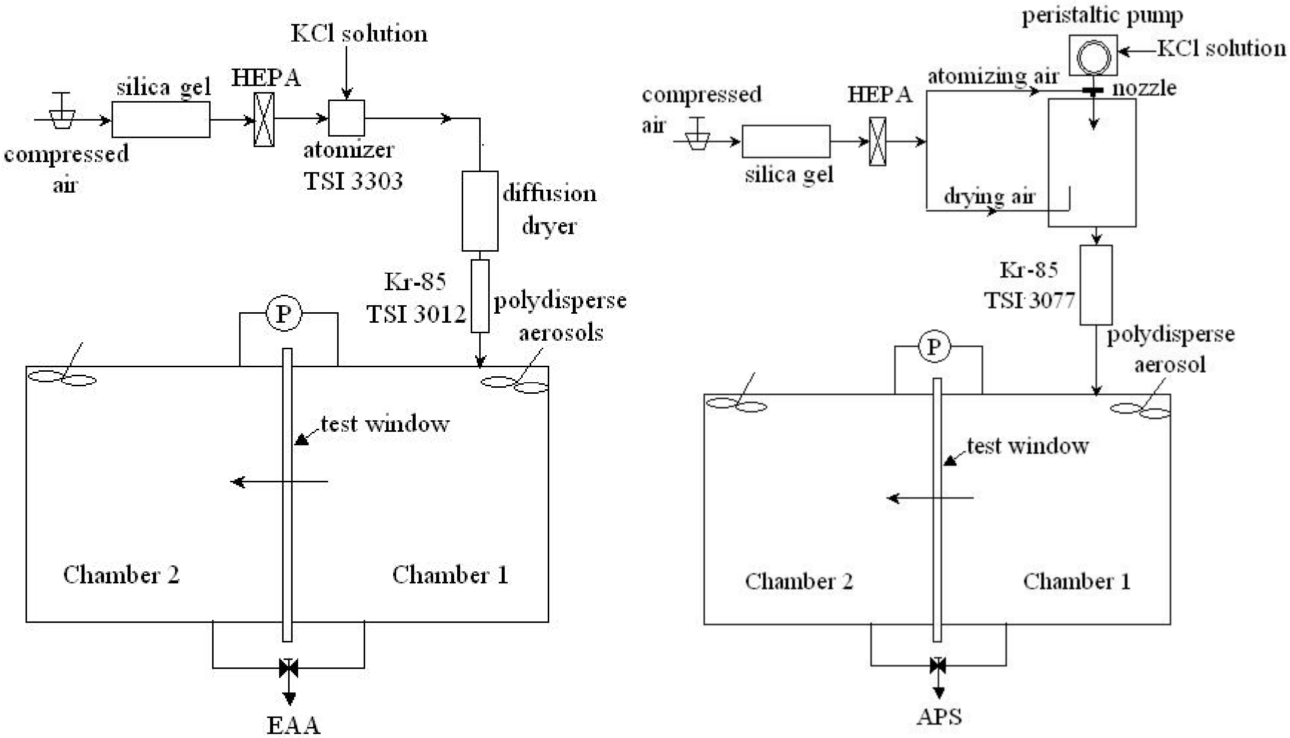
The finished window was mounted in a plywood panel so that all gaps between the window perimeter and the plywood were well sealed. Thus, the leakage paths within the window unit were the only air leakage pathways in these experiments. The window panel was inserted so that it separated the volumes of two identical plywood chambers (101.6 × 101.6 × 76.2 cm). A pressure difference (ΔP) of 1 Pa was created across the window by supplying air to chamber 1, some of which leaked into chamber 2. Both chambers were maintained at a net positive pressure to prevent uncontrolled particle infiltration from the laboratory. During the experiments, ΔP was monitored with a digital micromanometer (The Energy Conservatory, Minneapolis, MN, USA), which had been calibrated with a manometer (Microtector®, Model 1430, Dwyer Instruments Inc., IN, USA). A small fan was used to mix the air in each chamber.

The experimental scheme involves continuously introducing polydisperse particles into chamber 1, and monitoring the concentration versus time in both chambers. The change of particle concentration in chamber 2 with time can be represented by the following equation:

$$\frac{dC_2}{dt} = p\lambda_v C_1 - (\lambda_v + k_d)C_2 \tag{1}$$

where C_1 and C_2 are the particle concentrations in chambers 1 and 2 (number cm^{-3}), p is particle penetration factor (dimensionless) through the window, and λ_v and k_d are air exchange rate (h^{-1}) and particle deposition coefficient (h^{-1}) in chamber 2, respectively. Note that C_1 and C_2 are measured as functions of particle diameter (d_p). It is evident from equation (1) that the particle penetration factor can be inferred from $C_1(t)$, $C_2(t)$, λ_v, and k_d once these parameters have been determined. Particle penetration is determined as a function of particle diameter through the appropriate application of equation (1) to experimental data.

Figure 1 shows the experimental schematics. After airborne particles were generated from atomizers (TSI 3075, St. Paul, MN; and a custom-built unit), they were dried and electrically neutralized prior to entering the chamber. Aerosol concentrations in both well-mixed chambers were continuously measured using an Aerodynamic Particle Sizer (APS, TSI 3320, St. Paul, MN) and an Electrical Aerosol Analyzer (EAA, TSI 3030, St. Paul, MN). The particle sizes measured by the APS and EAA reflect aerodynamic and electrical mobility properties of the particles, respectively. Two sampling lines of identical length from chambers 1 and 2 met at a three-way valve, which was used to alternate the aerosol flow to the EAA or the APS. The air-exchange rate in chamber 2 was evaluated for each experiment by monitoring tracer gas (SF_6 or CO_2) concentration decay with time, using a multigas monitor (Type 1302, Brüel&Kjær, Denmark) or a CO_2 monitor (Telaire 7001, Engelhard, USA).



(a) (b)

Figure 1. Experimental schematics for the generation and measurement of (a) submicron (0.024-1 µm), and (b) supermicron (0.6-10 µm) particles.

RESULTS AND DISCUSSION

Particle loss rates

As shown in equation (1), air exchange and deposition onto chamber surface are the two particle removal mechanisms in chamber 2. To determine size-resolved particle loss rates under consistent airflow conditions, we performed a separate experiment that relies on measurement of size-specific, time-dependent particle concentration decay after a deliberate concentration increase. After particle concentration in chamber 2 was raised to a sufficient level, we stopped particle generation and monitored the concentration decay as particles were flushed out by particle-free air from chamber 1. Thus the overall particle loss rate ($\lambda_v + k_d$) can be determined by application of this equation:

$$\lambda_v + k_d = \frac{\ln(C_{2i}/C_{2t})}{t} \tag{2}$$

where C_{2i} and C_{2t} are the initial and final particle concentrations measured in chamber 2, and t is the measurement time interval (h). The air-exchange rate was obtained by a similar method, except that the particle concentrations in equation (2) were replaced with tracer-gas concentrations.

Penetration factor

The particle penetration factor is defined here to be the fraction of particles that remain airborne as air enters chamber 2 from chamber 1 through the leaks of the test window. Two methods are employed to evaluate particle penetration as a function of particle size. The first method assumes that a steady-state condition prevails. The penetration factor is inferred by measuring the size-resolved particle concentrations in both chambers in response to a constant supply of polydisperse particles to chamber 1. Solving equation (1) for steady-state conditions, we have

$$p = \frac{\lambda_v + k_d}{\lambda_v}\left(\frac{C_2}{C_1}\right) \qquad (3)$$

In the second method, the particle level in chamber 2 is first reduced to a negligible value by supplying particle-free air. Then, the increase of particle concentration is measured as polydisperse particles, supplied to chamber 1, penetrate through the window. We expect to see the growth of particle concentration in chamber 2 until it reaches the steady state, so we call the second approach the dynamic, concentration-growth method.

It is important to characterize the uncertainty associated with the experimentally determined penetration factors. A Monte-Carlo approach was applied to perform simulations, with the input parameters randomly sampled from normal distributions. The distribution means were designated as the experimentally determined values for air-exchange rate, particle deposition rate, and particle concentrations in both chambers, and the standard deviations were assigned so that the errors associated with the measurements were well described. To best evaluate the penetration factor from the concentration growth experiment, a least-square approximation was employed to fit the measured particle concentrations in chamber 2. In the study, thirty-two simulations were conducted for the uncertainty analysis in each experiment.

Figure 2 presents the calculated penetration factors from the simulations for Wr and Wc'. (The results for Wc agree closely with those for Wc'.) The solid symbols and the error bars indicate the average values of penetration factors and the ninety-five percent confidence interval, as determined by means of the dynamic, concentration growth method. The steady-state penetration factors, as determined from equation (3), are designated by open circles.

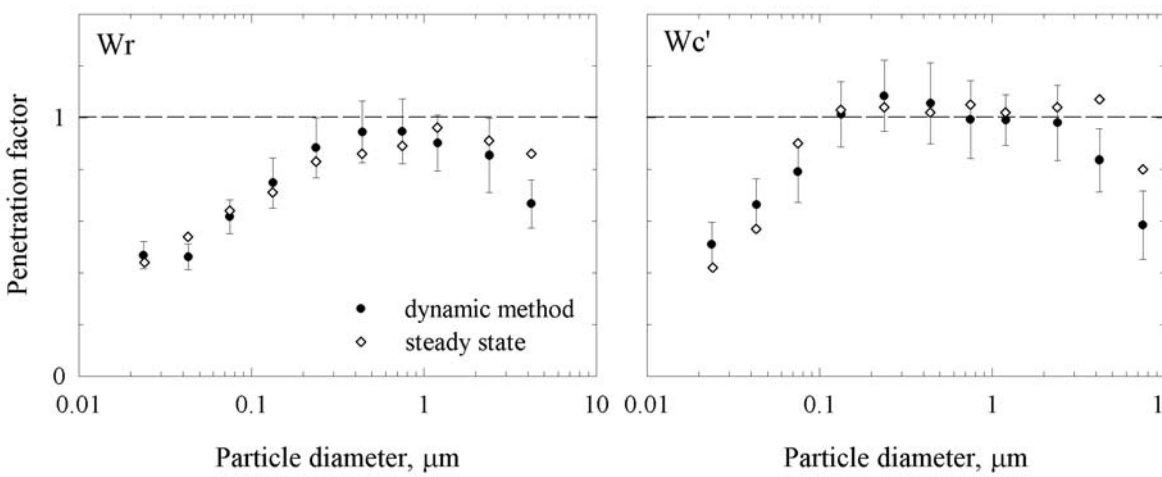


Figure 2. Particle penetration factors obtained for the two test windows from the steady state method, as well as the dynamic, concentration growth approach. Airflow through the window unit was induced by means of a steady pressure drop of 1 Pa. Penetration for particle diameters smaller than or larger than 1 μm were measured with the systems depicted in Figures 1(a) and 1(b), respectively. Particle concentrations in chamber 1 during these experiments ranged from 10 $cm^{=3}$ for 8 μm particles to ~ 80,000 cm^{-3} for 0.075 μm particles.

As seen in Figure 2, particle penetration exceeds 80 % for 0.2-3 μm in Wr, while complete penetration is observed for 0.2-3 μm in Wc'. This indicates that the airborne particles in these size ranges penetrate through the windows fairly effectively. For particles larger or smaller than these sizes, significant particle losses arise, probably as a result of gravitational settling and Brownian diffusion, respectively (Liu and Nazaroff, 2001). For example, about 50% of 0.02 μm particles are lost from air leaking through these windows. In terms of experimental reliability, it is reassuring that the penetration factors estimated from the steady-state method agree moderately well with those that are determined from the dynamic, concentration-growth method for each test window.

For the smaller particles tested, the residential class window without weatherstipping appears to allow fewer particles to penetrate than the commercial class window with weatherstripping. This was confirmed by running a *t*-test, which revealed that the penetration factors for Wr were significantly lower than for Wc (at the 0.05 probability level) for particles smaller than 0.4 μm and larger than 2 μm. For particles between 0.4 and 2 μm, penetration through the two windows exhibits no significant difference statistically. These observations may result from different distributions of leakage-path sizes in the two windows.

The *t*-test was also used to compare the penetration factors of submicron particles for the commercial window with an unsealed frame (Wc) and a tape-sealed frame (Wc'); no significant difference was found. This indicates any additional air leakage between the aluminum perimeter and the wooden frame did not play a role in fractional particle penetration. (For experiments using supermicron particles, only Wr and Wc' were tested, since similar results were expected for Wc and Wc'.) Note that air flows through a variety of window leakage paths, which possess a distribution of geometrical dimensions. The overall particle penetration factor for a window unit is the flow-weighted-average penetration through each opening. Consequently, it is the distribution of window leakage dimensions that determines the overall performance of particle penetration, rather than the leakage area per se. Furthermore, since particle penetration also results from air infiltrating through leaks of window/wall joints and adjacent wall cavities, overall wall construction quality is expected to be a factor in particle penetration. Based on these insights, to minimize ambient particle penetration into buildings, improvements are needed in all elements: window design, manufacturing, installation, and maintenance. Reductions in particle penetration through building component systems, such as windows, can serve to reduce human exposure to ambient particles.

Window leakage

The notion of effective leakage area, used to evaluate the air tightness of building components, can be applied to characterize the windows tested in these experiments. The effective leakage area can be calculated from the following expression (ASHRAE, 1993):

$$A = \frac{Q}{C_d}\left[\frac{\rho}{2\Delta P}\right]^{\frac{1}{2}} = \frac{\lambda_v V}{C_d}\left[\frac{\rho}{2\Delta P}\right]^{\frac{1}{2}} \tag{4}$$

where A is the effective (or equivalent) leakage area (m^2), ρ is air density (kg m^{-3}), Q is the air flow rate through the unit (m^3 h^{-1}), C_d is the discharge coefficient for the leakage openings (dimensionless), and V is the chamber volume (m^3). The value of C_d is usually taken as 0.6 (as for a sharp-edged rectangular opening), though it might vary in the range of 0.6-1, depending on leakage characteristics (Heiselberg et al., 2000). Since the window perimeter is well sealed to the surrounding panel in the experiments, air leakage is expected to occur only through the sash/frame joints of the window assembly. The approximate effective leakage areas for Wr and Wc' at $\Delta P = 1$ Pa are 1.1 and 2.2 cm^2/lms (leakage area per linear meter of sash), respectively. These values are comparable to the estimated effective leakage area (0.2 to 2.1 cm^2/lms) reported for single horizontal slider windows with weatherstripping (ASHRAE, 1993).The air leakage rate per unit frame area was also evaluated to compare with the ANSI/AAMA 101/I.S.2 guidelines (ANSI, 1999). We found the air leakage to be 2.1 and 4.2 $m^3\ h^{-1}\ m^{-2}$ for Wr and Wc, respectively, in compliance with the standard (5 $m^3\ h^{-1}\ m^{-2}$).

CONCLUSION

Laboratory experiments have been performed to investigate particle penetration through two windows. The penetration factors estimated from the steady-state method agree well with those determined from the dynamic, concentration-growth method. We have shown that more than 80% of particles in the diameter range 0.2-3 µm penetrate through either window. Penetration is lower for particles smaller or larger than this range. We point out that the overall particle penetration factor of a window assembly is determined by the distribution of leakage dimensions. Neither air-leakage area nor air-leakage rate, as aggregate terms that are commonly reported for assessing window air-tightness, are directly helpful in predicting fractional particle penetration. Although the small number of samples prevents us from drawing broad conclusions to apply to other window types, the results do provide some insight into expected values of particle penetration, especially when combined with our earlier modeling work (Liu and Nazaroff, 2001). Additional investigations along these same lines can improve our understanding of the factors that affect human exposure to particles of ambient origin. It is also conceivable that improved window assemblies could be developed that offer protection against exposure to ambient particles.

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